A New FDTD Method for the Study of MRI Pulsed Field Gradient-Induced Fields in the Human Body

Stuart Crozier, Huawei Zhao and Liu Feng
Centre For Magnetic Resonance, The University of Queensland, St. Lucia, Qld 4072, Australia

In modern MRI, patients are exposed to strong, rapidly switched magnetic field gradients that may be able to elicit nerve stimulation (1-14). This paper provides the numerical results of an investigation into induced current spatial distributions inside human tissue when exposed to these pulsed magnetic field gradients. Conventional FDTD methods are unable to model these effects as the effective frequencies of the input source are less than 100kHz or so, relatively low for FDTD calculations. A new High Definition FDTD variant was developed to operate over this bandwidth and a number of body and gradient models are analysed using the new method.

Introduction

When patients undergo a Magnetic Resonance Imaging (MRI) scan, they are subject to both strong static and temporal magnetic fields as well as radio-frequency fields. MRI is intended to be a non-invasive modality and any interaction between these fields and the patients must be well controlled and within safe limits. As MRI instrumentation moves towards the use of higher field strengths and faster scanning, the potential for field/patient interaction increases. There are a range of tissues that comprise the human body and each has a different frequency-dependent conductivity and permittivity; it is these properties that effect the interaction with electromagnetic fields. If the extent of the field/patient interactions could be better understood by experimentally validated theoretical models of the phenomena, then the equipment can be re-engineered with these limitations in mind. The resultant scanners would have both improved performance and better patient safety.

The temporal magnetic fields in an MR system are designed to vary at each point in the region being imaged. This is achieved by the use of gradient coils. However, when the gradient coils are switched very rapidly, the strong, time-varying magnetic fields produced can be responsible for stimulating nerves in the peripheral regions of the body (PNS). It is a major goal of this project to devise new methods for accurately modelling the effects of switched gradients on the human body and to further design new, clinically useful, gradient coils that minimize the risk of such stimulation.

Methods

Conventional FDTD methods proceed by repeatedly solving for a finite difference analogue of Maxwells equations within each cell of a defined lattice. They accomplish this by attempting to arrive at steady state behaviour for the **E** and **B** fields within each cell as a result of the tracking of an incident wave and its interactions with the medium. In a typical FDTD simulation, computational times on the order of a few periods of the source are required, limiting the method to high frequency analyses.

For low frequency problems, it is not feasible to run the conventional FDTD technique for a full period. For example, with a 100 Hz source incident on a biological model of isotropic resolution 10 mm, conventional FDTD stability criteria would result in a computation time of about 100 years! To obtain the solution within a fraction of the source period, a new time-frequency conversion method has been developed. Using the proposed new HD-FDTD technique, only a finite number of solutions are needed in the time domain, and then an inverse approach can be used to calculate A_i and ϕ_i. If the source electromagnetic field is represented in Time-Harmonic form, each of the harmonics may be calculated using FDTD in a relatively straightforward fashion.

Assuming that the source field consists of sinusoidal components of frequencies ω_1,

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Abstract

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$\omega_2, \cdots, \omega_n$, then the field (magnetic or electric) can be represented at each temporal point as

$$f(\mathbf{r},t) = \sum_{i=1}^{n} A_i(\mathbf{r}) \sin(\omega_i t + \phi_i(\mathbf{r}))$$

In order to obtain the solution in a very small fraction of the period of the source, a new time-frequency conversion technique has to be adopted. The amplitude and phase terms are the unknowns to be found. Assuming that the transient response will die out after L_p loops, and the corresponding iteration number is $L_p \times L_1$. When $N_{it} \geq L_p \times L_1$, the time dependent solutions s_1, $s_2, \cdots, s_m$ will be recorded at the times $t_1, t_2, \cdots, t_m$. In general, $m \geq 2n$, and the complete system may be represented as:

$$\begin{cases} s_1 = \sum_{i=1}^{n} A_i \left(\sin\phi_i \cos(\omega_i t_1) + \cos\phi_i \sin(\omega_i t_1)\right) \\ s_2 = \sum_{i=1}^{n} A_i \left(\sin\phi_i \cos(\omega_i t_2) + \cos\phi_i \sin(\omega_i t_2)\right) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ s_m = \sum_{i=1}^{n} A_i \left(\sin\phi_i \cos(\omega_i t_m) + \cos\phi_i \sin(\omega_i t_m)\right) \end{cases},$$

In our proposed method, only a finite number of solutions are needed in time domain, and then an inverse approach is used to calculate A_i and ϕ_i at each frequency. To verify the model, HD-FDTD calculations based a one-dimensional plane wave incident on a single, lossy (conductive) dielectric material were made and compared with analytical solutions (see figure 1).

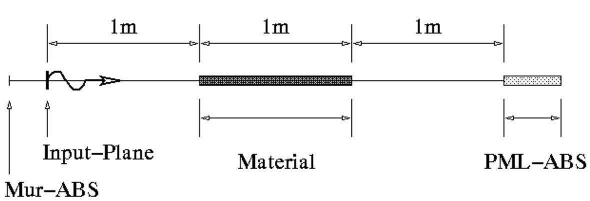

Fig. 1 – The test problem

In order to test the absorbing boundary conditions, Mur's first order absorbing boundary is used to absorb the reflected wave and Berenger's PML is used to absorb the transmitted wave. $\varepsilon = 80$ and $\sigma = 0.5$ were used for the material. The space was broken into 1 cm elements. According to the stability criterion, for one completed loop (one forward and backward path), 635 iterations are required. Two source frequencies, 50 Hz and 100 kHz, were tested. The results of the convergence history are given in figure 2, where figure 2 (a) and (b) present field amplitude and phase solutions for f = 100 kHz. The solution for f = 50 Hz showed slightly better correlation. The solutions are calculated for 1 loop, 5 loops, 10 loops and 30 loops, in which the iteration number are 635, 3175, 6350 and 19050 respectively. The accuracy of the solutions obtained after 30 loops indicates that the algorithm is very accurate at low frequency and that both absorbing boundaries performed efficiently. The computational time on a single processor Sun Enterprise 450 was < 1second for this simple problem.

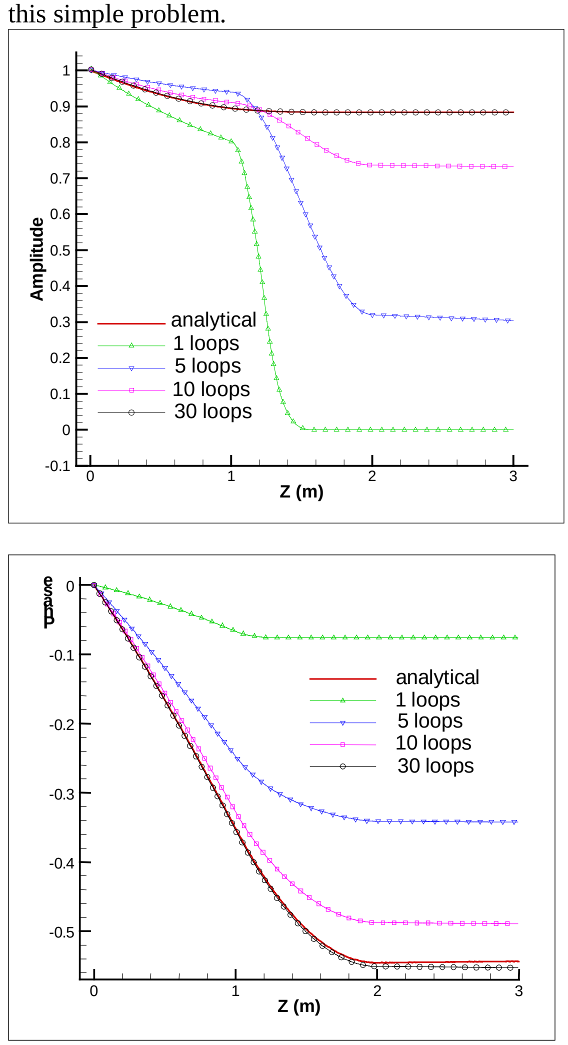

Fig.2 The magnetic field amplitude (top) and phase (bottom) results for the test problem. Note the excellent convergence after 30 loops.

Results – Human Body Simulation

The human body model (Fig. 3) was positioned centrally in a magnet system with a Maxwell-coil pair z-gradient coil. A complete human body model with frequency dependent electrical parameters (ε,σ,μ), was used. The inner surface of magnet was treated as perfect conductor wall. A PML absorbing boundary, which truncates computational domain, is used to surround the human body. A 2.5 kHz current source $J_{in} = J_0 \sin(2\pi f \times t)$ was used to drive a Maxwell-coil pair gradient set. In this system, isotropic 1cm resolution was used, representing a large mesh. After the HD-FDTD algorithm was run for 40,000 iterations, the eddy current density was obtained from the E-field solution. The solutions required approximately 5 hours of parallel processing on a 4-processor Sun Enterprise 450. A representation of the eddy current density in X-Y cross-sections covering the model is shown in figure 4 .

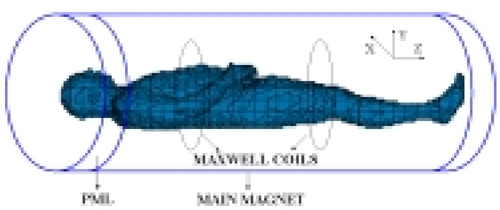

Figure 3 – The body position

Conclusion

The comprehensive preliminary results shown above for the calculation of induced fields show considerable promise as an aid to better understanding of the interaction between the pulsed gradient fields generated in an MR scanner and the human body.

E8 References

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Figure 4 – The induced current (A/m^2) in various parts of the body model, resulting from a sinusoidal gradient of peak amplitude 40 mT/m.